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Role of coronal mass ejections in the heliospheric Hale cycle

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[1] The 11-year solar cycle variation in the heliospheric magnetic field strength can be explained by the temporary buildup of closed flux released by coronal mass ejections (CMEs). If this explanation is correct, and the total open magnetic flux is conserved, then the interplanetary-CME closed flux must eventually open via reconnection with open flux close to the Sun. In this case each CME will move the reconnected open flux by at least the CME footpoint separation distance. Since the polarity of CME footpoints tends to follow a pattern similar to the Hale cycle of sunspot polarity, repeated CME eruption and subsequent reconnection will naturally result in latitudinal transport of open solar flux. We demonstrate how this process can reverse the coronal and heliospheric fields, and we calculate that the amount of flux involved is sufficient to accomplish the reversal within the 11 years of the solar cycle. **Citation:** Owens, M. J., N. A. Schwadron, N. U. Crooker, W. J. Hughes, and H. E. Spence (2007), Role of coronal mass ejections in the heliospheric Hale cycle, *Geophys. Res. Lett.*, **34**, L06104, doi:10.1029/2006GL028795.

1. Introduction

[2] The solar cycle evolution of the Sun's magnetic field, notably the solar field polarity reversal, is driven by the interior solar dynamo interacting with the differential rotation of the solar plasma [Babcock, 1961; Leighton, 1969]. At the photosphere, this results in mid-latitude magnetic flux emergence, which gradually migrates to the polar regions, eventually bringing about the polarity reversal [e.g., Schrijver *et al.*, 2002; Wang *et al.*, 2002, and references therein]. In the heliosphere the field reversal is morphologically different, appearing to occur as a simple rotation of a dipole field, with a single large-scale heliospheric current sheet (HCS) prevailing throughout [Jones *et al.*, 2003]. The magnetically dominated corona links these two disparate regions, though the processes responsible for the necessary solar cycle restructuring of the corona are not well understood and form the focus of this study.

[3] Wang and Sheeley [2003] use axisymmetric potential field solutions to show how emerging mid-latitude dipoles cause closed coronal loops to rise and destroy/create open flux in such a way as to reverse the coronal field. Successive steady-state potential field solutions to the corona are used to infer the effect of evolving photospheric fields, describing how the minimum energy state of the corona changes, but not how the corona transitions between these states.

[4] It has also been suggested that the heliospheric field reversal proceeds as a simple rotation of the HCS [Fisk *et*

al., 1999], due to continual reconnection between open and closed flux at the coronal hole boundaries. In this scenario, coronal holes can rigidly rotate despite the differential rotation of the photosphere and of the underlying magnetic flux, and open flux is not purely confined to the interiors of coronal holes. Fisk and Schwadron [2001] propose that HCS rotation is driven by a diffusive process (called media diffusion) involving reconnection between open and closed field lines (interchange reconnection) [Crooker *et al.*, 2002].

[5] Coronal mass ejections (CMEs) may play a critical role in the evolution of the large-scale coronal magnetic field, acting as sinks of newly emerged flux and helicity [Low, 2001; Lynch *et al.*, 2005, and references therein]. Observationally, Gopalswamy *et al.* [2003] noted a correspondence between the cessation of high latitude CMEs and the polar field reversal. Furthermore, Low [2004] suggested that coronal mass ejections may bodily remove old open solar flux from the corona for replacement by new open flux of opposite polarity, thus participating in the coronal global field reversal.

[6] On the basis of observed CME rates and ICME flux estimates, Owens and Crooker [2006] recently demonstrated that the doubling of the heliospheric unsigned magnetic flux over the solar cycle can be explained by a temporary buildup of closed ICME flux, provided the characteristic timescale for the ICME flux opening is long (~ 40 –50 days). The closed flux of ICMEs must either be balanced by opening the ICME flux via interchange reconnection [Crooker *et al.*, 2002], which conserves and reconfigures open flux, or by conserving the ICME closed flux but disconnecting open flux [McComas *et al.*, 1992]. Both these processes must occur below the solar wind Alfvén point in order to reconfigure heliospheric flux. Either method is able to explain observed abundance rates of counterstreaming suprathermal electron (CSE) and electron dropout signatures at 1 AU [Owens and Crooker, 2007]. However, observations of sunward-directed suprathermal electron strahls [e.g., Crooker *et al.*, 2004b] and the slight decrease in CSEs associated with magnetic clouds between 1 and 5 AU [Crooker *et al.*, 2004a; Riley *et al.*, 2004] both favour interchange reconnection. Furthermore, heliospheric flux returns to the same value each solar minimum [e.g., Arge *et al.* 2002], which is direct evidence of open flux conservation over the solar cycle. If the open flux is not conserved throughout the solar cycle, then open-flux creation must exactly balance open-flux destruction (i.e., disconnection), by some unknown mechanism. Although observations of coronal inflows [e.g., Sheeley and Wang, 2002] have been cited as evidence of disconnection, they could as well be evidence of the interchange reconnection that opens ICMEs.

[7] In this study, we bring together key observational aspects of CMEs and heliospheric magnetic flux to demonstrate how ejecta can reconfigure the global coronal and

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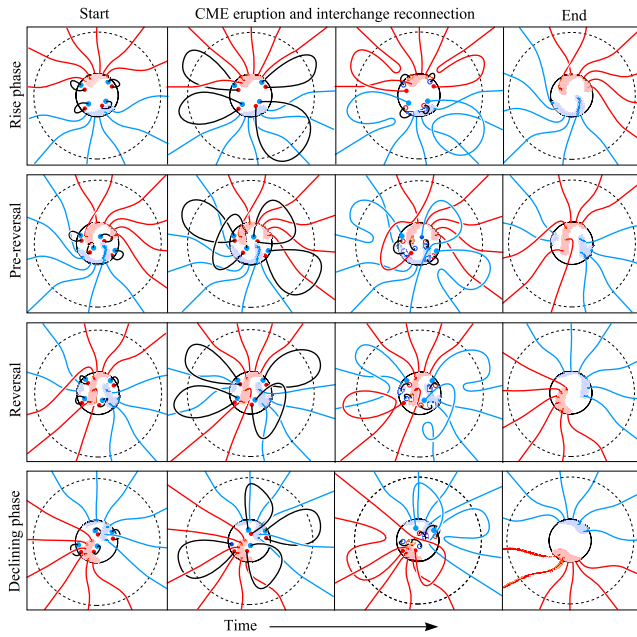


Figure 1. A sketch of the topological evolution of the solar magnetic field. Black dashed lines show a heliocentric distance past which field lines are considered “open” to the heliosphere. Light red (blue) shaded regions are negative (positive) polarity coronal holes (CHs), whereas red (blue) lines are the associated inward (outward) magnetic field lines. Black lines show the closed CME loops, with the red (blue) circles showing the negative (positive) polarity CME footpoints. Negative (positive) open flux that has interchange reconnected to produce closed loops is shown as white regions with red (blue) outlines. See the main text for description.

heliospheric fields in response to the solar cycle changes in the photospheric field, leading to a complete field reversal without the need for destruction of open flux.

2. The Model

[8] In this section we outline the chain of logic leading to our model of the coronal field reversal. We begin by assuming that open solar flux (i.e., flux that does not close within the heliopause) is conserved, though the flux threading a heliocentric sphere can vary with the addition of closed flux to the heliosphere, as in the model of *Owens and Crooker* [2006]. With this assumption, closed ICME flux must open via interchange reconnection with open flux below the solar wind Alfvén point and each CME eruption must therefore move the interchanged open flux by at least the CME foot-point separation.

[9] Using in-ecliptic observations, *Bothmer and Rust* [1997] and *Bothmer and Schwenn* [1998] found that the magnetic field polarity of filaments and associated magnetic clouds obeys a trend similar to the Hale law for sunspot polarity [*Hale and Nicholson*, 1925], where the polarity of the leading (in the sense of solar rotation), lower latitude sunspot is determined by the dominant hemispheric polarity at the start of the solar cycle. The Hale cycle for CME footpoints is supported by *Ulysses* observations of magnetic

clouds over solar cycle 23 [*Rees and Forsyth*, 2003]. Here it comprises our second assumption. When coupled with the assumption of conserved open flux, repeated CME eruption and subsequent interchange reconnection must lead to a net latitudinal transport of open solar flux and, hence, reverse the polarity of the coronal and heliospheric magnetic field.

[10] In Section 3 we show that as long as our two assumptions are met, the amount of open flux transported in this way must provide a significant contribution to that required for the coronal field reversal. The remainder of this section details how interchange reconnection should proceed over the solar cycle to provide the required flux transport.

[11] Figure 1 shows a sketch of the proposed topological evolution of the solar magnetic field. Horizontal strips follow in sequence from the top of the page. The black dashed lines show a heliocentric distance past which field lines are considered “open” to the heliosphere. Light red (blue) shaded regions are negative (positive) polarity coronal holes (CHs), whereas red (blue) lines are the associated inward (outward) magnetic field lines. Black lines show the closed CME loops (though they are “open” from a solar perspective once they pass the Alfvén point), with the red (blue) circles showing the negative (positive) polarity CME footpoints. Negative (positive) open flux that has interchange reconnected to produce closed loops is shown as white regions with red (blue) outlines. Figure 2 shows the equivalent process in the form of photospheric synoptic maps, in the same format.

[12] The solar cycle shown is analogous to cycle 22, with the start of the cycle characterised by negative open flux from the north pole of the Sun, and positive from the south. Following *Bothmer and Rust* [1997], *Bothmer and Schwenn* [1998], and *Rees and Forsyth* [2003], northern (southern) hemisphere CMEs have a negative (positive) leading footpoint, which is positioned closer to the equator than the trailing footpoint throughout the whole cycle.

[13] The reversal process has been separated into three stages: a rise phase, a reversal phase (further broken into pre-reversal and reversal in Figures 1 and 2) and a declining

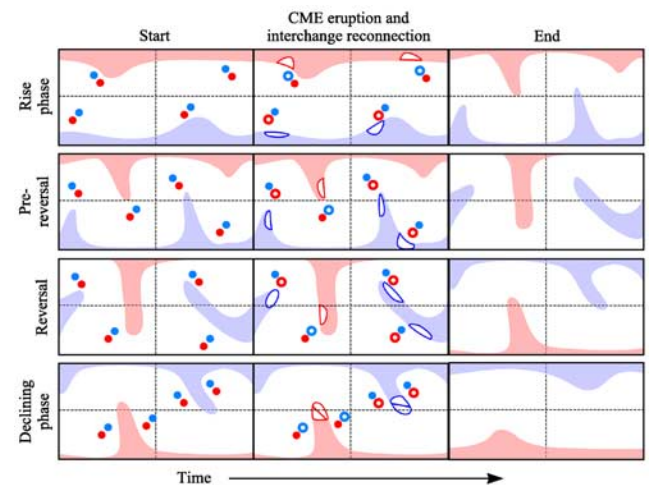


Figure 2. A sketch of the coronal hole and CME footpoints at the photosphere, in the form of a synoptic map. Same format as Figure 1.

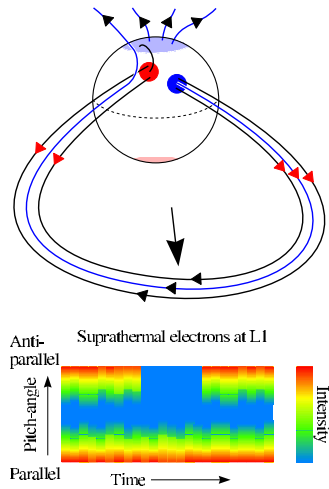


Figure 3. A sketch of ICME flux opening and observable signatures in suprathermal electrons measurements in the heliosphere. For solar cycle 23, which began with positive (blue) polarity flux in the northern hemisphere, the rising phase should be characterised by the negative (red) polarity CME footpoint opening. Black (red) arrows show the magnetic field (electron heat flux) direction. In situ observations (bottom panel) of the resulting magnetic cloud would reveal a mixture of counterstreaming suprathermal electrons (for ICME field lines yet to open) with dropouts in the anti-parallel strahl. Southern hemisphere ICMEs should see dropouts in the parallel strahl. This effect should switch in the declining phase.

phase. These stages are ordered on the basis of the CH-CME interactions that preferentially occur:

[14] Rise phase: Open field lines in polar CHs predominantly interchange reconnect with closed field lines in CMEs from one hemisphere. The poleward CME footpoint opens, resulting in an equatorward transport of open flux (see also Figure 3). This phase ends with equatorial extensions of the CHs.

[15] Reversal phase: The equatorial CH extensions allow open field lines in CHs to interchange reconnect with closed fields in CMEs from both hemispheres. CH flux still in the original hemisphere continues to be transported toward the equator, while CH flux that has crossed the equator is transported toward the opposite pole. Figures 1 and 2 illustrate a switch in dominance of these two types of interchange reconnection between the pre-reversal and reversal stages. Either CME footpoint may open during this phase. Although the model dictates open-flux transport across CME footpoints, it does not constrain how the open flux is organised at the time of the field reversal.

[16] Declining phase: Open field lines in CHs again predominantly interchange reconnect with closed fields in CMEs from one hemisphere. However, it is now the equatorward CME footpoint that opens, resulting in a poleward transport of open flux.

[17] The net effect is to transport the open solar flux from one pole to the other, bringing about the coronal (and hence heliospheric) field reversal. The next section shows that the amount of flux transported by this process is sufficient to

account for the coronal polarity reversal within the observed 11 year solar cycle.

3. Flux Estimate

[18] To assess quantitatively the feasibility of the model, it is necessary to estimate the magnetic flux carried by a typical ICME (ϕ). This parameter is loosely constrained observationally [e.g., *Lynch et al.*, 2005]. It is instructive to investigate what further limitations can be placed on ϕ .

[19] Assuming that the magnitude of the radial component of the heliospheric magnetic field is constant over a heliocentric sphere [*Smith and Balogh*, 2003; *Lockwood et al.*, 2004], the change in heliospheric unsigned flux over the solar cycle is given by $\sim 4\pi R^2 |\Delta \mathbf{B}| \cos 45^\circ$, where R is 1 AU and $|\Delta \mathbf{B}|$ is the difference in the magnetic field intensity at 1 AU between solar minimum and maximum, observed to be ~ 3 nT [e.g., *Owens and Crooker*, 2006], and 45° is the nominal Parker spiral angle at 1 AU. Thus the solar cycle flux increase is $\sim 6 \times 10^{14}$ Wb, which we assume to be entirely due to the temporary addition of closed ICME flux (i.e., true open flux is constant, though the flux threading a heliocentric sphere may vary). At solar minimum $|\mathbf{B}| \sim 5$ nT, suggesting the true open flux, Φ_0 , is $\sim 1 \times 10^{15}$ Wb. Counterstreaming electrons (CSEs) are indicators of closed heliospheric magnetic flux [*Gosling et al.*, 1987]. As CSEs are routinely seen within magnetic clouds at 5 AU [e.g., *Riley et al.*, 2004; *Crooker et al.*, 2004a], and typical ICME speeds are ~ 450 km/s, the minimum time for ICME flux opening must be ~ 20 days. For typical CME rates of 3 per day ($\sim 10,500$ CMEs observed by LASCO between January 1996 and January 2006, with approximately 4 months of data gaps) [*Yashiro et al.*, 2004] this allows at least 60 CMEs to contribute to the heliospheric flux content at any one instant on average. Hence the maximum value of ϕ is 1×10^{13} Wb, in rough agreement with the best observational estimate of $\phi = 3 \times 10^{12}$ Wb, made on the basis of force-free flux rope fits to a large number of magnetic cloud observations at 1 AU [*Lynch et al.*, 2005]. These numbers can be used to estimate the time-scale for a polarity reversal by open flux interchange reconnection with ICMEs.

[20] A complete reversal of the coronal field requires the total open solar flux, Φ_0 , to be transported through 180° , so as to proceed as a simple rotation of the HCS (see also Figures 1 and 2). If each CME moves ϕ of open flux by an angular distance equal to the latitudinal separation of the CME footpoints, d , the pole reversal requires N CMEs with Hale's law helicities, where:

$$N = \frac{\Phi_0 180^\circ}{\phi d} \quad (1)$$

[21] If the CME frequency is f , this leads to a solar field reversal timescale, τ , of:

$$\tau = \frac{\Phi_0 180^\circ}{f \phi d} \quad (2)$$

[22] Using the best (maximum) estimate of the average CME flux of $\phi = 3 \times 10^{12}$ ($= 1 \times 10^{13}$) Wb, with $\Phi_0 = 1 \times 10^{15}$ Wb and $f = 3 \text{ day}^{-1}$, the observed solar cycle length of

11 years can be brought about as long as the latitudinal CME footpoint separation is $\geq 5^\circ$ (2°).

4. Discussion

[23] The CME-driven coronal field reversal model of Low [2001, 2004] involves a destruction of pre-existing open solar flux, shrinking the coronal holes, before the corona is replenished with open flux of the new cycle. It is therefore topologically different from the model presented in this study, which involves open flux transport across CME footpoints, which are systematically oriented to result in the field reversal. Conversely, the emerging dipoles and associated quasi-static rising coronal loops of Wang and Sheeley [2003] are topologically similar to the coronal mass ejections invoked for the coronal field reversal in this study. Furthermore, relaxing the axisymmetric approximation of Wang and Sheeley [2003] to allow for a three-dimensional interaction of fields may result in interchange reconnection between the loops and the open flux, rather than a disconnection/creation of open flux. This would then lead to a conservation of open solar flux. Our model differs from Wang and Sheeley [2003], as well as that of Fisk and Schwadron [2001], in that CMEs rather than ambient loops provide the source for the large amount of flux required to reverse the open field (discussed further below). The dynamic nature and configuration of CMEs makes them ideal drivers of the required interchange reconnection, both during CME initiation and propagation through interplanetary space. Indeed, in situ suprathermal electron observations of magnetic clouds suggest approximately half the flux contained in a CME interchange reconnects during its formation and launch [Riley *et al.*, 2004; Crooker *et al.*, 2004a].

[24] Rather than ask why CMEs should provide the necessary reconnection, the issue can be approached from the opposite direction: If the assumptions of open flux conservation and CME footpoint configuration are met, how much flux transport does interchange reconnection with closed field lines in ICMEs provide over the solar cycle? Quantitatively, we find this process is adequate to account for the entire coronal polarity reversal if the average latitudinal CME footpoint separation is $\geq 2-5^\circ$. However, we note that this number assumes all CMEs have the required footpoint configuration. In situ observations suggest this is only true for $\sim 75\%$ of magnetic clouds [Bothmer and Rust, 1997; Bothmer and Schwenn, 1998; Rees and Forsyth, 2003]. Furthermore, magnetic clouds constitute only $\sim 30\%$ of all ICMEs, and it is not known whether non-cloud ICMEs contain similar amounts of flux and obey the same Hale law for footpoint configuration. Both these factors could raise the required minimum latitudinal CME footpoint separation and/or lower the percentage of the total open flux transport provided by CMEs. CME footpoints are difficult to observe directly, with coronal dimmings regions arguably providing the best proxy for their position. Although double dimmings showing both footpoints are rare, those reported seem to agree with our estimate for the minimum latitudinal CME footpoint separation [e.g., Thompson *et al.*, 1998]. Thus, open flux transport by CMEs can play a significant role in the coronal field reversal.

[25] A number of aspects of this model can be observationally tested. Perhaps most directly, during both the rising and

declining phases there should be a hemispheric dependence to the leg of the ICME that opens. This is readily sensed with suprathermal electron measurements of ICMEs, which give the polarity of open fields within them. In the rise phase of cycle 23, northern hemisphere ICMEs should contain a mixture of counterstreaming suprathermal electrons and dropouts in the anti-parallel strahl, while southern hemisphere ICMEs should see dropouts in the parallel strahl. This effect should switch in the declining phase (see Figure 3). Observations of the 12 May 1997 CME and resulting magnetic cloud at L1 show the correct configuration, both in the CME footpoint orientation and the polarity of the open leg of that particular magnetic cloud [Crooker and Webb, 2006]. Observations of many more events are required.

[26] Finally we note the need to further reconcile the evolution of the driving photospheric flux with the coronal and heliospheric flux. In particular, how does the observed poleward migration of active region photospheric flux [e.g., Schrijver *et al.*, 2002; Wang *et al.*, 2002] relate to the successive equatorward then poleward transport of open flux proposed here? Furthermore, how significant are the differential and meridional photospheric flows on the evolution of open flux [e.g., Fisk and Schwadron, 2001] and CME footpoint configurations? The approach taken by Luhmann *et al.* [1999] and Wang and Sheeley [2003], wherein successive steady-state potential field solutions to the corona are used to infer the effect of evolving photospheric fields, may be one way to proceed. However, we note that the photospheric field, and hence the potential field solution to the corona, is essentially unchanged before and after CME eruption and interchange reconnection, meaning potential field solutions should be carefully interpreted in the context of our field reversal model.

[27] In summary, we have shown that if open magnetic flux interchange reconnects with most of the magnetic flux released by CMEs, then CMEs will drive the reversal of the heliospheric magnetic field, playing a critical role in reconfiguring the open magnetic flux over the solar cycle.

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